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Yan et al.

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(54) **FLEXIBLE GRID TWDM-PON ARCHITECTURE AND INTELLIGENT SET-UP FOR TWDM-PON**

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(51) **Int. Cl.**

H04B 10/00	(2013.01)
H04J 14/02	(2006.01)
H04B 10/27	(2013.01)
H04J 14/08	(2006.01)

(52) **U.S. Cl.**

CPC ***H04J 14/0223*** (2013.01); ***H04B 10/27*** (2013.01); ***H04J 14/0282*** (2013.01); ***H04J 14/08*** (2013.01)

(58) **Field of Classification Search**

USPC 398/66–73

See application file for complete search history.

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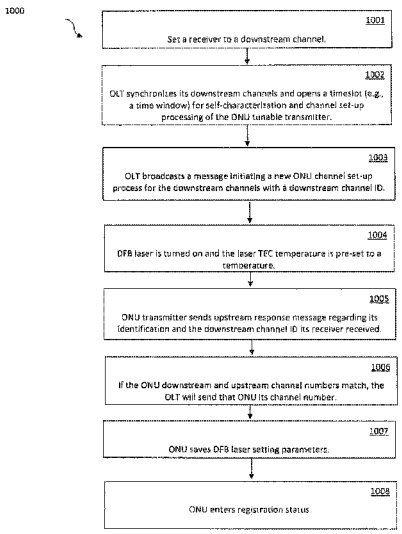
(57) **ABSTRACT**

An approach to proving a flexible grid architecture for time and wavelength division multiplexed passive optical networks is described. One embodiment includes an optical transmitter array configured to transmit an optical signal, an optical combiner coupled to the optical transmitter array configured to receive unlocked wavelengths from the optical transmitter array and output a single optical signal, and an optical amplifier coupled to the optical combiner configured to boost downstream optical power. In some embodiments, a WDM filter is coupled to the optical amplifier, and a tunable optical network units (ONUs) coupled to the WDM filter configured to transmit and receive the optical signals. In still other embodiments, a cyclic demultiplexer is coupled to the optical splitter and connects to an optical receiver array configured to receive optical signals.

13 Claims, 12 Drawing Sheets



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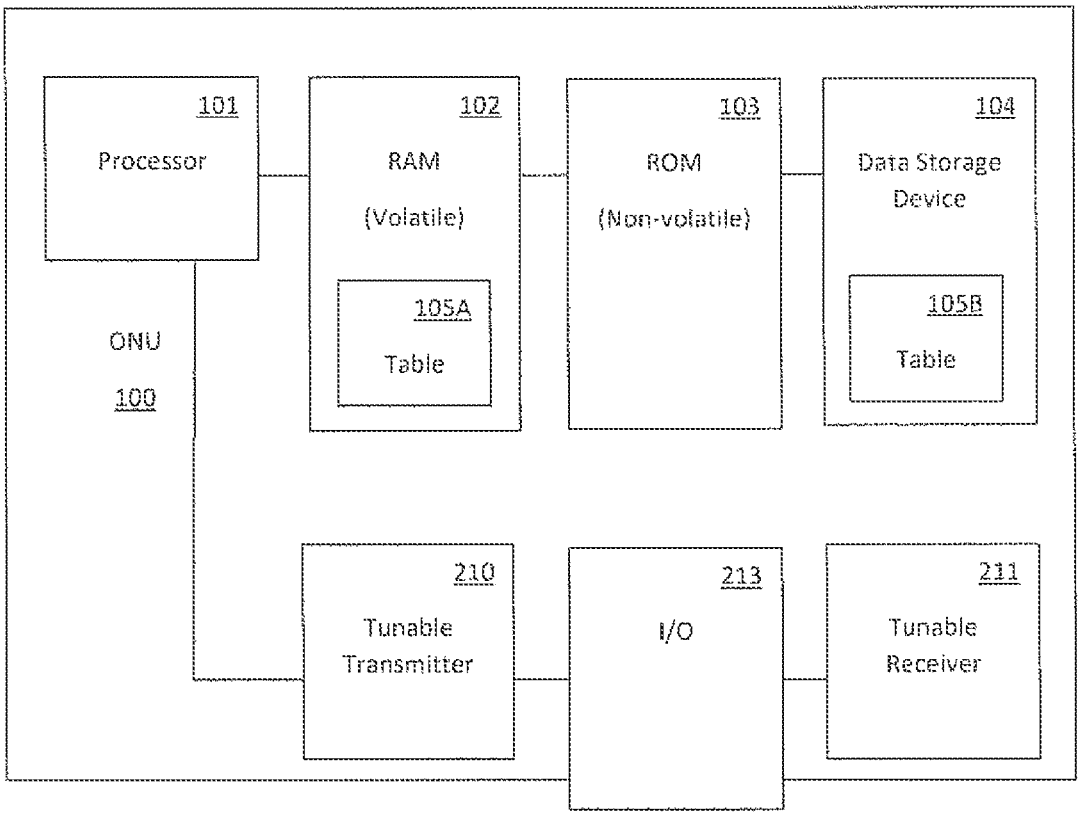
101
Processor
102
RAM
(Volatile)
105A
Table
103
ROM
(Non-volatile)
104
Data Storage
Device
105B
Table
ONU
100
210
Tunable
Transmitter
213
I/O
211
Tunable
Receiver

FIG. 1

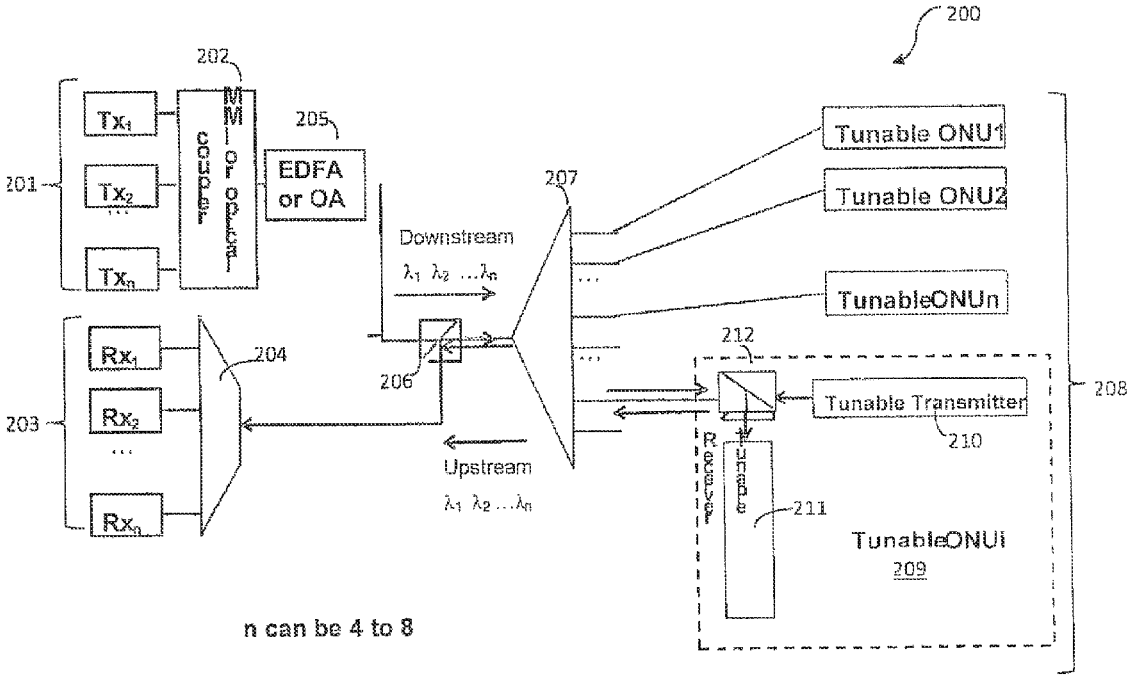
200
202
201
Tx1
Tx2
Txn
205
EDFA or OA
Downstream
λ1 λ2 ...λn
207
Tunable ONU1
Tunable ONU2
TunableONUn
212
208
Tunable Transmitter
210
Receiver
Tunable
211
TunableONUi
209
203
Rx1
Rx2
Rxn
204
206
Upstream
λ1 λ2 ...λn
n can be 4 to 8

FIG. 2

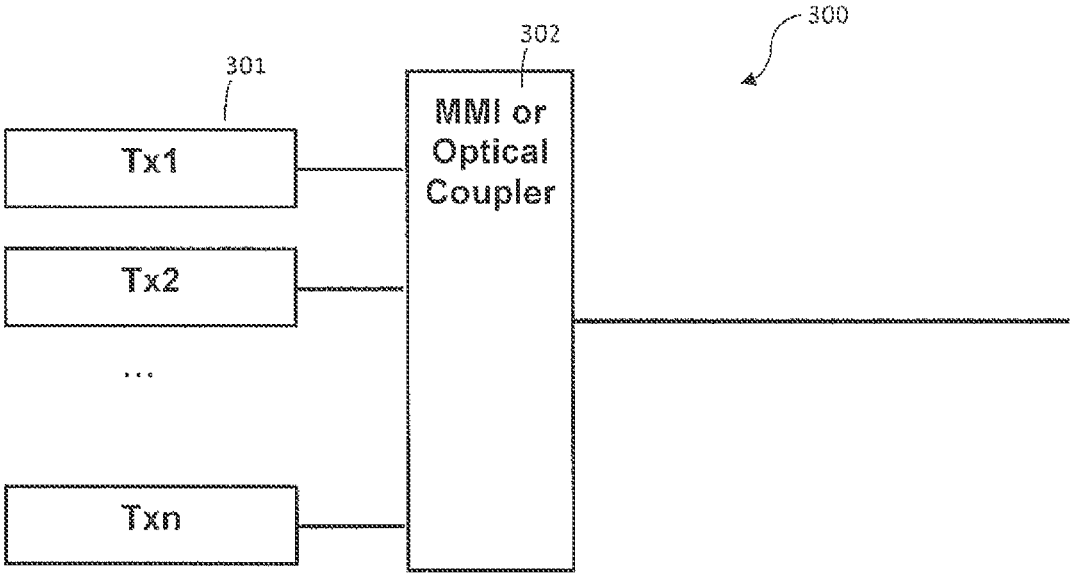

FIG. 3

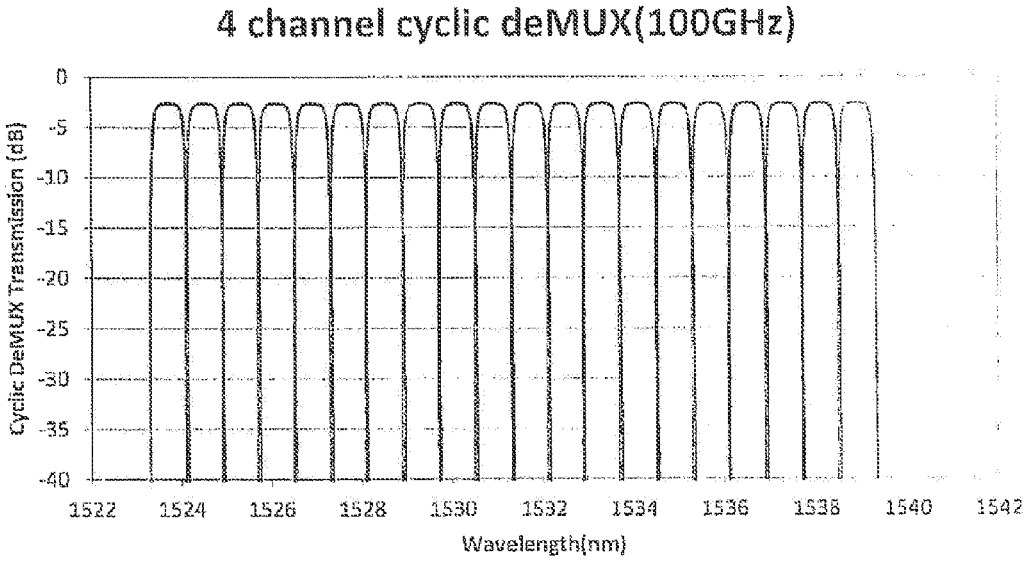
4 channel cyclic deMUX(100GHz)
Cyclic DeMUX Transmission (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
1522
1524
1526
1528
1530
1532
1534
1536
1538
1540
1542
Wavelength(nm)

FIG. 4

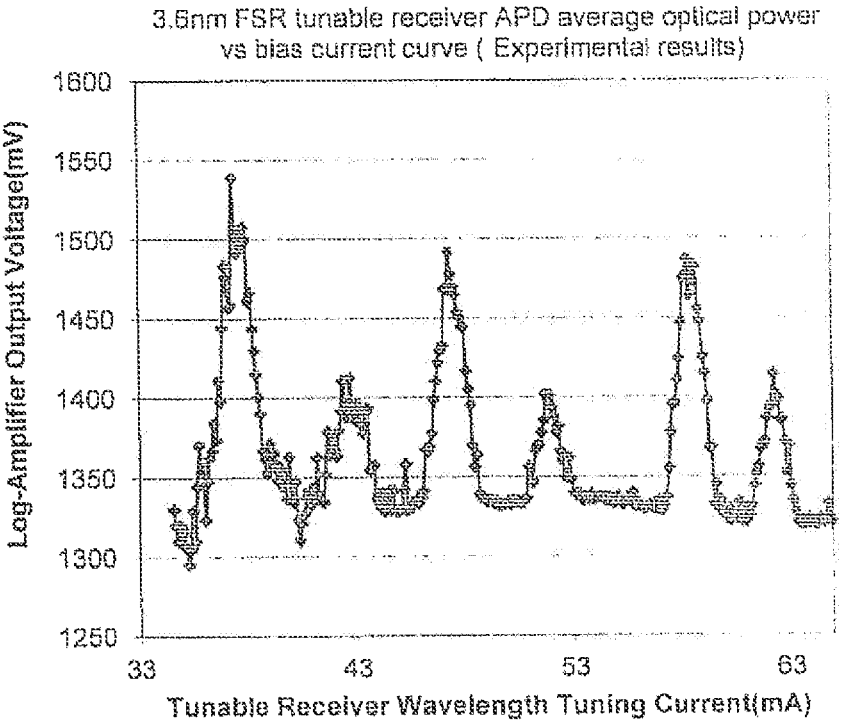
3.6nm FSR tunable receiver APD average optical power vs bias current curve (Experimental results)
Log-Amplifier Output Voltage(mV)
1600
1550
1500
1450
1400
1350
1300
1250
33
43
53
63
Tunable Receiver Wavelength Tuning Current(mA)

FIG. 5

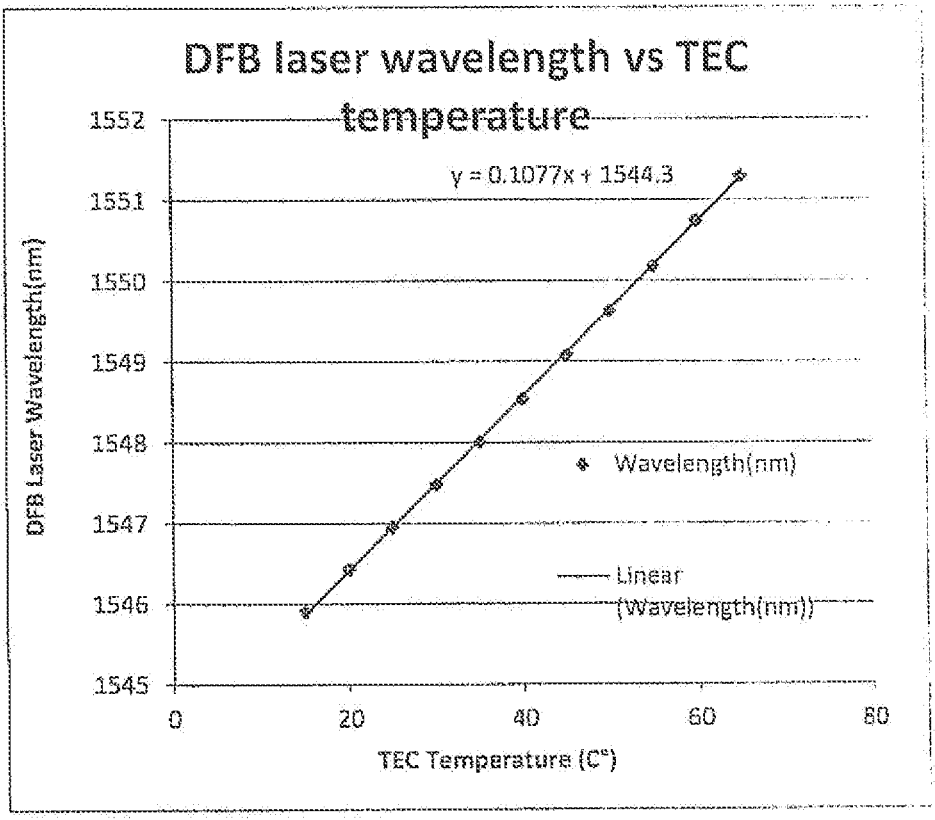
DFB laser wavelength vs TEC temperature
y = 0.1077x + 1544.3
DFB Laser Wavelength(nm)
1552
1551
1550
1549
1548
1547
1546
1545
0
20
40
60
80
TEC Temperature (C°)
Wavelength(nm)
Linear (Wavelength(nm))

FIG. 6

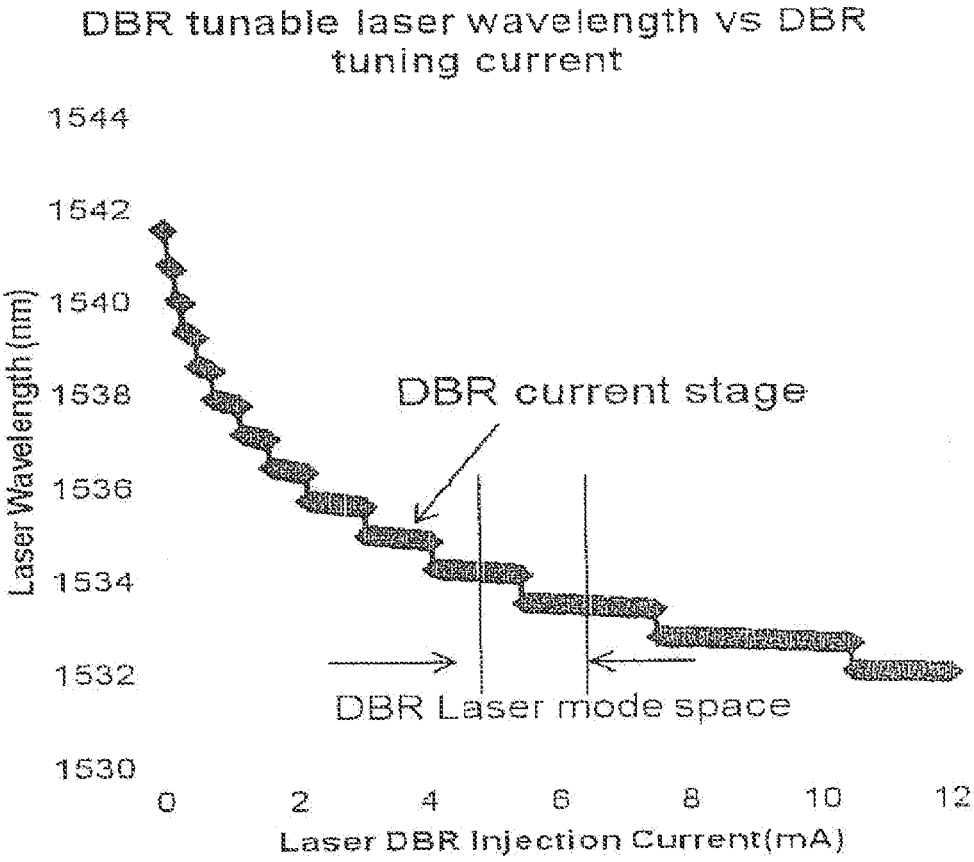
DBR tunable laser wavelength vs DBR tuning current
1544
1542
1540
1538
1536
1534
1532
1530
Laser Wavelength (nm)
DBR current stage
DBR Laser mode space
0
2
4
6
8
10
12
Laser DBR Injection Current(mA)

FIG. 7

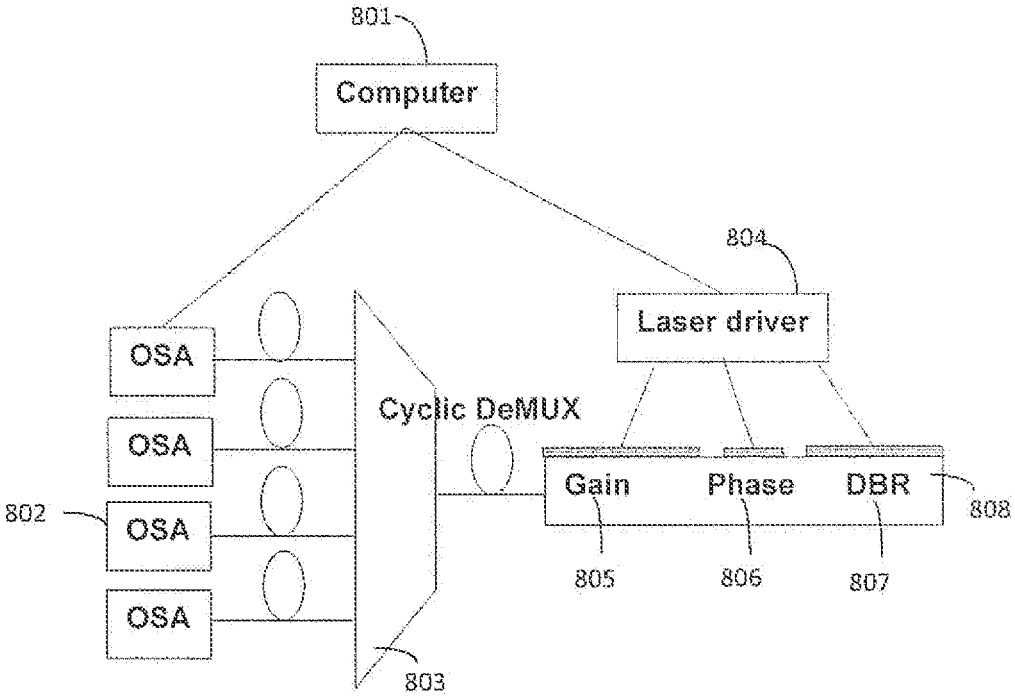
801
Computer
804
Laser driver
OSA
OSA
OSA
OSA
802
Cyclic DeMUX
Gain
Phase
DBR
808
805
806
807
803

FIG. 8

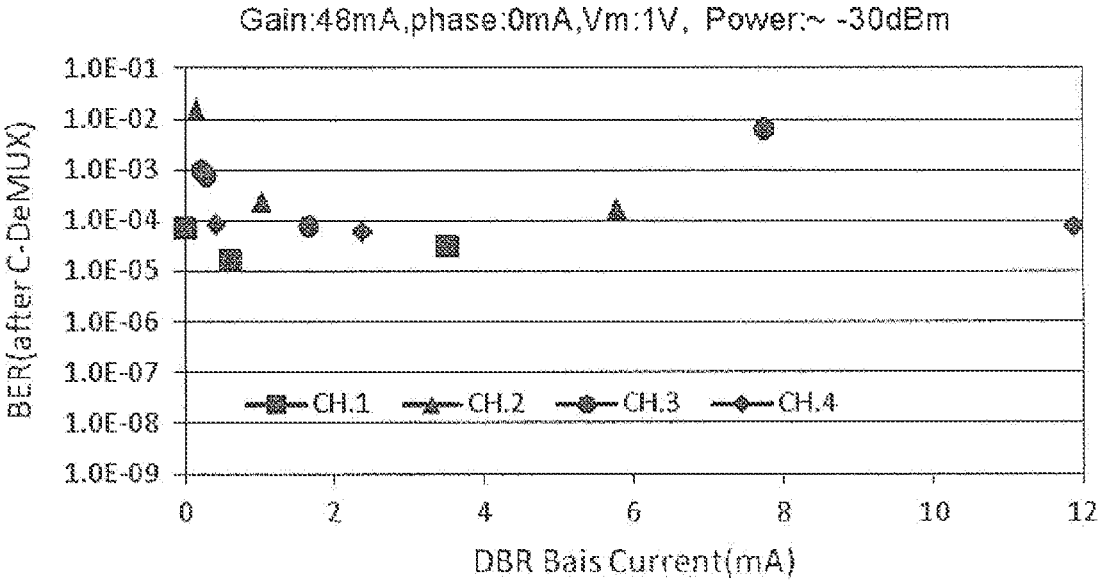
Gain:48mA,phase:0mA,Vm:1V, Power:~ -30dBm
BER(after C-DeMUX)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
CH.1
CH.2
CH.3
CH.4
0
2
4
6
8
10
12
DBR Bais Current(mA)

FIG. 9

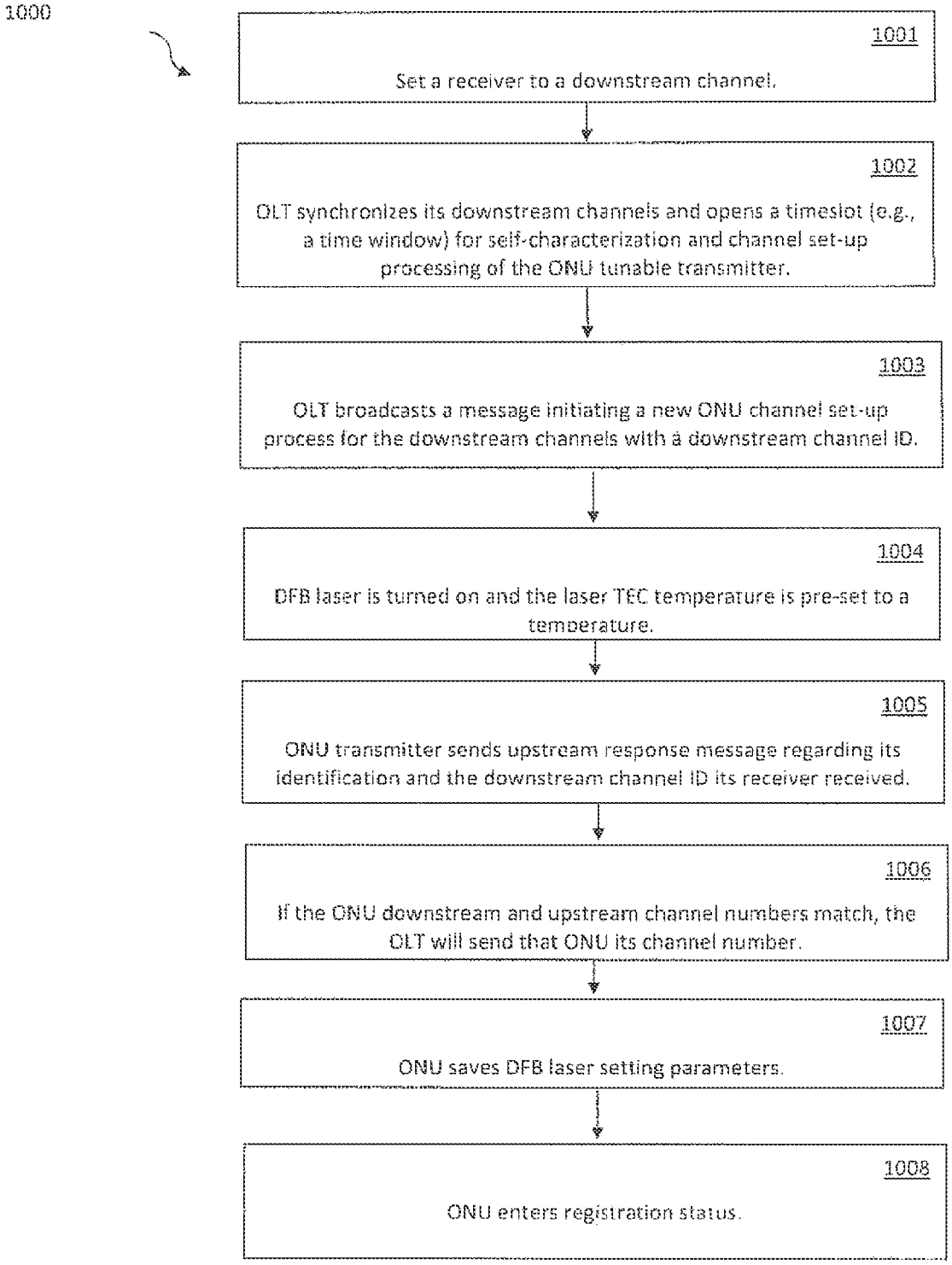
1000
1001
Set a receiver to a downstream channel.
1002
OLT synchronizes its downstream channels and opens a timeslot (e.g., a time window) for self-characterization and channel set-up processing of the ONU tunable transmitter.
1003
OLT broadcasts a message initiating a new ONU channel set-up process for the downstream channels with a downstream channel ID.
1004
DFB laser is turned on and the laser TEC temperature is pre-set to a temperature.
1005
ONU transmitter sends upstream response message regarding its identification and the downstream channel ID its receiver received.
1006
If the ONU downstream and upstream channel numbers match, the OLT will send that ONU its channel number.
1007
ONU saves DFB laser setting parameters.
1008
ONU enters registration status.

FIG. 10

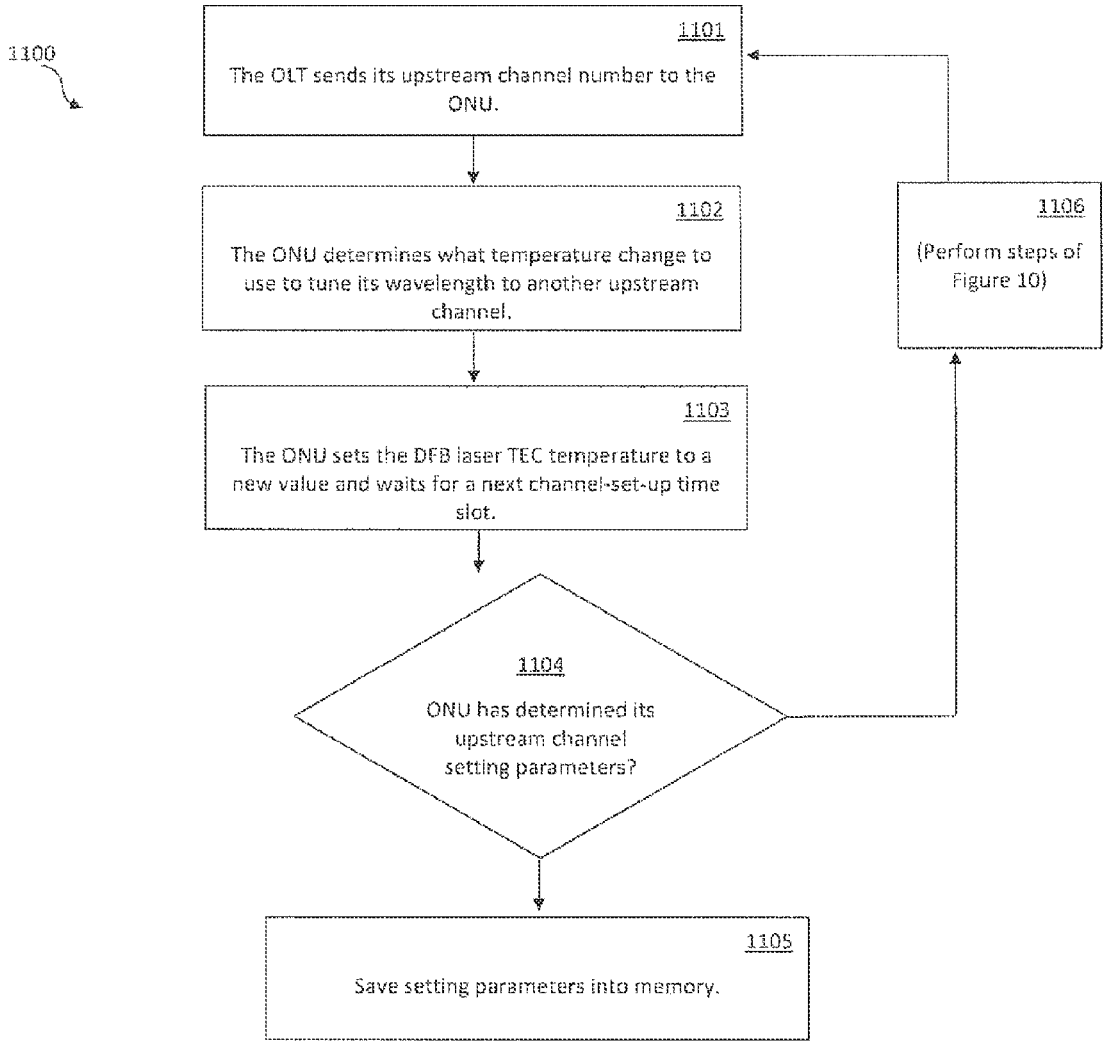
1100
1101
The OLT sends its upstream channel number to the ONU.
1102
The ONU determines what temperature change to use to tune its wavelength to another upstream channel.
1103
The ONU sets the DFB laser TEC temperature to a new value and waits for a next channel-set-up time slot.
1104
ONU has determined its upstream channel setting parameters?
1105
Save setting parameters into memory.
1106
(Perform steps of Figure 10)

FIG. 11

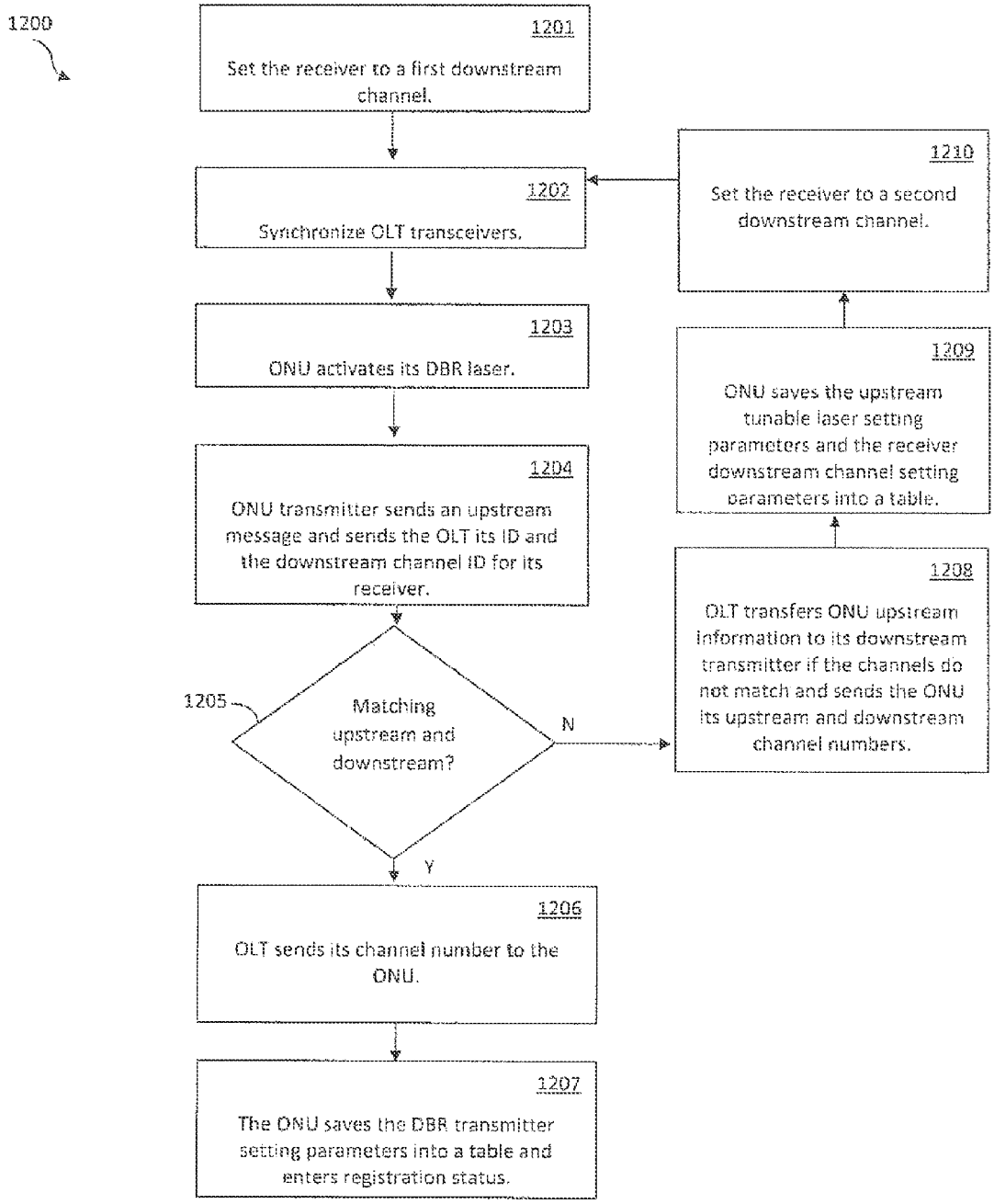
1200
1201
Set the receiver to a first downstream channel.
1202
Synchronize OLT transceivers.
1203
ONU activates its DBR laser.
1204
ONU transmitter sends an upstream message and sends the OLT its ID and the downstream channel ID for its receiver.
1205
Matching upstream and downstream?
N
Y
1206
OLT sends its channel number to the ONU.
1207
The ONU saves the DBR transmitter setting parameters into a table and enters registration status.
1208
OLT transfers ONU upstream information to its downstream transmitter if the channels do not match and sends the ONU its upstream and downstream channel numbers.
1209
ONU saves the upstream tunable laser setting parameters and the receiver downstream channel setting parameters into a table.
1210
Set the receiver to a second downstream channel.

FIG. 12

FLEXIBLE GRID TWDM-PON ARCHITECTURE AND INTELLIGENT SET-UP FOR TWDM-PON

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority to provisional application Ser. No. 61/903,593, filed on Nov. 13, 2013, entitled "FLEXIBLE GRID TWDM-PON ARCHITECTURE" naming the same inventors as in the present application. The contents of the above referenced provisional application are incorporated by reference, the same as if fully set forth herein.

FIELD

The present invention generally relates to the field of passive optical networks. More specifically, the present invention relates to providing a flexible grid passive optical network architecture.

BACKGROUND

A passive optical network (PON) is one type of optical access network for providing network access over "the last mile" of service. A PON is a point-to-multipoint network includes an optical line terminal (OLT) at a central office (CO), a plurality of optical network units (ONUs) at the user premises, and an optical distribution network (ODN) connecting the OLT and the ONUs. PONs may also include remote nodes (RNs) located between the OLTs and the ONUs, for example, at the end of a road where multiple users reside.

TWDM-PON stands for time and wavelength division multiplex passive optical networks. TWDM-PON is used for fiber to the home (FTTH) or FTTX, where X can be a premises, curb, or drop point, for example. In a TWDM-PON system, multiple wavelengths will be used for downstream and upstream transmission. For each wavelength, time division will be used; for multi-wavelengths, wavelength division will be used. There are Wavelength Division Multiplexers and Demultiplexers at the central office to combine downstream multi-wavelengths into a fiber and separate upstream multi-wavelengths into different receivers. At customer side, downstream wavelengths are transmitted to all tunable ONUs, and the tunable receiver of the ONU will pick up one wavelength from the downstream wavelengths. For upstream multi-wavelength light, which comes from tunable transmitters of the ONUs, the demultiplexer will separate the multi-wavelength light to different channel receivers at the OLT side.

Many PONs presently use wavelength division multiplexers to combine optical signals into a fiber for transmission. This approach introduces significant cost and complexity as new devices are added or deleted and the topography of the network changes. Also, this approach fails to provide automatic channel alignment and channel set-up for downstream and upstream channels at the system level.

SUMMARY

In one embodiment, an apparatus for performing time and wavelength division multiplexing is disclosed, the apparatus includes an optical transmitter array having a first optical transmitter and a second optical transmitter configured to transmit an optical signal, an optical combiner coupled to the optical transmitter array configured to receive the optical signal from the optical transmitter array and output a multi-wavelength optical signal, and an optical amplifier coupled to the optical combiner configured to boost downstream optical power, where the optical combiner is configured to receive a first optical signal having a first wavelength and a second optical signal having a second wavelength different from the first wavelength, and where an output of the first optical transmitter and an output of the second optical transmitter having intermediate grid wavelength values.

Some embodiments further provide a WDM filter coupled to the optical amplifier, and one or more tunable optical network units (ONUs) coupled to the WDM filter configured to transmit and receive optical signals, where the WDM filter is configured to selectively transmit downstream messages generated by the optical transmitter array and selectively transmit upstream signals generated by the one or more tunable ONUs. Other embodiments further provide a cyclic demultiplexer coupled to the optical splitter having a passband width and a rejection band width, and an optical receiver array coupled to the cyclic demultiplexer configured to receive optical signals from the WDM filter, where the passband width of the cyclic demultiplexer is larger than the rejection band width of the cyclic demultiplexer.

In another embodiment, a method of performing online receiver characterization for a tunable optical network unit (ONU) having matching upstream and downstream channels is described. The method includes tuning an optical receiver of an ONU to one of the downstream channels, then another downstream channel, until finish all downstream channel characterization. After that, ONU tunable receiver sets its filter to one of the downstream channels to receive OLT broadcasting registration or channel checking signal with downstream channel ID.

In another embodiment, a method of performing channel checking and matching for a tunable optical network unit having different upstream and downstream channels is described. The method includes receiving a first channel number from an optical line terminal (OLT) at a tunable ONU, tuning the downstream channel of the tunable ONU based on the first channel number, waiting for a channel checking and matching message, determining if the downstream channel and upstream channel of the tunable ONU are the same channel number, and if the downstream channel and upstream channel of the tunable ONU are the same channel number, entering registration status at the tunable ONU. If the downstream channel and upstream channel of the tunable ONU are not the same channel number, transferring upstream information from the tunable ONU to the OLT, where the upstream information relates to an ONU receiving channel, receiving a second channel number from the OLT, tuning the tunable ONU based on the second channel number and the upstream information, entering registration status at the tunable ONU.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form a part of this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention:

FIG. **1** is a block diagram of an exemplary ONU having a processor and memory according to embodiments of the present invention.

FIG. **2** is a diagram illustrating an exemplary flexible grid TWDM-PON diagram according to embodiments of the present invention.

FIG. **3** is a diagram illustrating an exemplary downstream transmitter array diagram according to embodiments of the present invention.

FIG. **4** is a graph of an exemplary wide pass-band cyclic demultiplexer spectra according to embodiments of the present invention.

FIG. **5** is a graph of experimental tunable receiver online characterization results according to embodiments of the present invention.

FIG. **6** is a graph of experimental DFB laser wavelength results with TEC temperature changing according to embodiments of the present invention.

FIG. **7** is a graph of experimental DBR laser wavelength tuning and hopping results with DBR bias current increasing according to embodiments of the present invention.

FIG. **8** is a diagram illustrating an exemplary upstream channel experimental set-up schematic according to embodiments of the present invention.

FIG. **9** is a chart illustrating exemplary DBR tunable laser upstream channel alignment results for 4 channels according to embodiments of the present invention.

FIG. **10** is a flow chart illustrating an exemplary ONU DFB Tunable Transmitter Self-characterization and Channel Set-Up procedure according to embodiments of the present invention.

FIG. **11** is a flow chart illustrating an exemplary ONU DFB Tunable Transmitter Self-characterization and Channel Set-Up procedure according to embodiments of the present invention, where Downstream and Upstream are not at the same channel.

FIG. **12** is a flow chart illustrating an exemplary ONU tunable transmitter channel set-up procedure according to embodiments of the present invention.

DETAILED DESCRIPTION

Reference will now be made in detail to several embodiments. While the subject matter will be described in conjunction with the alternative embodiments, it will be understood that they are not intended to limit the claimed subject matter to these embodiments. On the contrary, the claimed subject matter is intended to cover alternative, modifications, and equivalents, which may be included within the spirit and scope of the claimed subject matter as defined by the appended claims.

Furthermore, in the following detailed description, numerous specific details are set forth in order to provide a thorough understanding of the claimed subject matter. However, it will be recognized by one skilled in the art that embodiments may be practiced without these specific details or with equivalents thereof. In other instances, well-known methods, procedures, components, and circuits have not been described in detail as not to unnecessarily obscure aspects and features of the subject matter.

Portions of the detailed description that follows are presented and discussed in terms of a method. Although steps and sequencing thereof are disclosed in a figure herein describing the operations of this method, such steps and sequencing are exemplary. Embodiments are well suited to performing various other steps or variations of the steps recited in the flowchart of the figure herein, and in a sequence other than that depicted and described herein.

Some portions of the detailed description are presented in terms of procedures, steps, logic blocks, processing, and other symbolic representations of operations on data bits that can be performed on computer memory. These descriptions and representations are the means used by those skilled in the data processing arts to most effectively convey the substance of their work to others skilled in the art. A procedure, computer-executed step, logic block, process, etc., is here, and generally, conceived to be a self-consistent sequence of steps or instructions leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated in a computer system. It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like.

It should be borne in mind, however, that all of these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise as apparent from the following discussions, it is appreciated that throughout, discussions utilizing terms such as "accessing," "writing," "including," "storing," "transmitting," "traversing," "associating," "identifying" or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

Some embodiments may be described in the general context of computer-executable instructions, such as program modules, executed by one or more computers or other devices. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Typically the functionality of the program modules may be combined or distributed as desired in various embodiments.

Flexible Grid TWDM-PON Architecture

In the following embodiments, techniques for proving a flexible grid architecture for time and wavelength division multiplexed passive optical networks are described. One described embodiment includes an optical transmitter array configured to transmit multi-wavelength optical signals, an optical combiner couples the optical transmitter array output light into one waveguide or one fiber, and an optical amplifier coupled to the optical combiner output configured to receive unlocked wavelengths from the optical transmitter array and output a multi-wavelength optical signal, and configured to boost downstream optical power. In some embodiments, a wavelength division multiplexing (WDM) optical filter is coupled to the optical amplifier configured to separate or combine downstream and upstream optical signals and pass a portion of the downstream signals to an optical splitter and reflect upstream optical signals to a demultiplexer coupled to the optical filter. One or more tunable optical network units coupled to the optical splitter are configured to transmit and receive optical signals. In still other embodiments, a cyclic demultiplexer is coupled to the optical filter and connects to an optical receiver array configured to receive optical signals.

Features of the present invention provide TWDM-PON systems that are more cost-effective, flexible, reliable, and manageable. One key feature relaxes the downstream and upstream wavelength grid to bring the system's optical module cost down, while at same time making the system more flexible, manageable, and intelligent. FIG. **2** depicts an

exemplary flexible grid TWDM-PON schematic diagram according to some embodiments.

With regard to FIG. **1**, an exemplary Optical Network Unit (ONU) **100** is depicted according to embodiments of the present invention. ONU **100** includes a processor (e.g., a general purpose process or a network processor) coupled to RAM **102**, ROM **103**, and Data storage device **104** for storing data. Table **105**A of RAM **102** and Table **105**B of Data storage device **104** may be used to store upstream and/or downstream channel setting parameters. As discussed in greater detail below, channel setting parameters may comprise gain, phase, DBR current, and/or TEC temperature channel settings. Input/output (I/O) **213** may be used to send and receive optical signals using tunable receiver **211** and/or tunable transmitter **210**.

With regard now to FIG. **2**, an exemplary TWDM-PON system **200** is depicted according to embodiments of the present invention. A downstream transmitter array **201** of the TWDM-PON system **200** is coupled to a multimode interface (MMI) or optical combiner **202**. The downstream transmitter array **201** comprises one or more transmitters (e.g., transmitters Tx1, Tx2, . . . Txn). According to some embodiments of the present invention, the transmitters (e.g., transmitters Tx1, Tx2, . . . Txn) comprise OLT (optical line terminal) transceivers. For a four-downstream wavelength transmitter array, monolithic integration multi-wavelength transmitter array with an MMI (or Star) coupler may be used and offers advantages over using an AWG multiplexer. An MMI coupler size is much smaller than an AWG multiplexer size, and package costs are much lower because only one fiber to the array output waveguide is used. The MMI and optical couplers are not wavelength sensitive optical combiners, and they are configured to combine each channel into an output waveguide regardless of wavelength. The coupling efficiency of the laser output power to the optical fiber is similar to using an AWG multiplexer. This potentially lowers the transmitter cost.

For an eight-downstream channel transmitter array, laser output power may be raised by increasing laser length. For a 10 Gb/s data rate, the laser is biased at a static current value. The mode size converter is integrated with the laser array to enhance the array coupling efficiency from the output waveguide to the fiber.

An optical amplifier **205** (e.g., an Erbium Doped Fiber Amplifier) is added to boost downstream optical power. The output of the optical amplifier **205** passes through WDM filter **206** to optical splitter **207**. WDM filter **206** directs optical signals to and from tunable ONU array **208**, and optical splitter **207** splits optical signals for tunable ONUs. Tunable ONU array **208** comprises one or more tunable ONUs (e.g., Tunable ONU 1, Tunable ONU 2, Tunable ONU n, Tunable ONU i). As illustrated by exemplary Tunable ONU i (**209**), a tunable ONU comprises a tunable transmitter **210** and a tunable receiver **211**. The tunable transmitter **210** and a tunable receiver **211** may be coupled to an optical splitter or a WDM filter **212** for sending and receiving data over an optical signal.

For demultiplexer **204**, it may be desirable for its passband width to be larger than its rejection band width. For example, the demultiplexer may be cyclic and its 1 dB passband width may be larger than 60% of the channel space. Therefore, with a 100 GHz channel space, its passband width may be greater than or equal to 60 GHz. The adjacent channel rejection ratio should be larger than 20 dB.

A wide passband cyclic demultiplexer has several advantages compared to a regular cyclic demultiplexer. There is a higher chance of ONU upstream wavelength falling into any channel passband even without laser wavelength characterization. Also, it is insensitive to small drifts of the upstream wavelength and has much larger tolerance for tunable laser wavelength tuning accuracy. Optical receiver array **203** comprises one or more receivers (e.g., receivers Rx1, Rx2, . . . Rxn) and receives the output of demultiplexer **204**, which may comprise a wide passband cyclic demultiplexer.

FIG. **3** depicts an exemplary downstream transmitter array diagram according to embodiments of the present invention. The multi-wavelength transmitter array **300** comprises multi-discrete transmitters (e.g., multi-discrete transmitters **301**) or a monolithic integration laser array with a modulator array and an MMI or Optical coupler **302**. The wavelengths do not need to be on the grid (e.g., intermediate grid wavelengths) and the laser wavelength values do not need to be locked in at any position. In other words, for a laser position in the array, the wavelength can be different from one laser array to another.

Tunable Receiver Self-Characterization of Flexible Grid TWDM-PON ONU

Because OLT multi-channel transmitter array wavelengths may not have a specific value for each channel and may be any value within the wavelength range, such as a ±0.2 nm range off the grid, the ONU tunable receiver may use online characterization for its downstream channel position setting. According to some embodiments of the present invention, a tunable receiver consists of a thermal tuning tunable filter, a regular receiver, filter wavelength tuning circuits, and average optical power monitor circuits. When changing the filter heating current, the filter transmission peak moves and the average optical power at the receiver changes. When the filter peak matches a downstream wavelength, the average power reaches its peak. When increasing heating current continuously, the filter peak moves away from that channel and the average optical power decreases. When the peak moves close to the wavelength of the next channel, the average optical power increases. When the peak matches the next channel wavelength, the average optical power reaches yet another peak.

FIG. **5** shows tunable receiver online characterization results according to one embodiment. According to the depicted embodiment, there are four downstream wavelengths with a 10 Gb/s data rate for each wavelength. Because the tunable filter is a cyclic filter and its free spectral range (FSR) is about 3.6 nm at 1550 nm wavelength, six peaks are detected. In the example of FIG. **5**, the first peak is channel 1, the second peak is channel 2, the third peak is channel 3, the fourth peak is channel 4, the fifth is channel 1, and sixth peak is channel 2. This data is saved into the receiver memory and an ONU microcontroller processes the data and locates the tunable filter bias current values for the downstream channels which correspond to peak average optical power. The filter bias current values for downstream channels are saved into receiver memory for filter channel setting and switching.

Tunable DFB Transmitter on-Line Characterization of Flexible Grid TWDM-PON ONU

According to some embodiments of the present invention, a DFB (Distributed Feedback) laser used for tunable ONU on-line characterization has the following specifications. First, the DFB laser wavelength falls into 1520 nm to 1540 nm range; such as: $1522 \leq \lambda \leq 1538$ (TEC: 30 C.°). Second, the DFB laser has average optical power: ≥4 dBm (TEC: 65 C.°). Third, the side mode suppression ratio (Side-Mode Suppression Ratio (SMSR): ≥RF signal on): ≥30 dB (for TEC temperature tuning range; such as, 20 to 65 C.° range).

The following sections A-F disclose online characterization procedures for a tunable DFB laser based ONU according to embodiments of the present invention.

Section A: ONU DFB Tunable Transmitter Self-Characterization and Channel Set-Up (with Down and Upstream Using the Same Channel).

With regard to FIG. **10**, a flow chart illustrating an exemplary ONU DFB Tunable Transmitter Self-characterization and Channel Set-Up procedure **1000** is depicted according to embodiments of the present invention. According to some embodiments, the channel checking and matching procedures begin by setting a receiver to one of the downstream channels (step **1001**). The OLT synchronizes its downstream channels and opens a timeslot (e.g., a time window) for self-characterization and channel set-up processing of the ONU tunable transmitter (step **1002**). The OLT broadcasts a message initiating a new ONU channel set-up process for the downstream channels with a downstream channel ID (step **1003**). After the new ONUs receive the message, the DFB laser is turned on and the laser TEC temperature is pre-set to a predetermined temperature (e.g., 35 C.°) (step **1004**). The ONU transmitter sends upstream response message regarding its identification and the downstream channel ID that its receiver received (step **1005**). The OLT compares the downstream and upstream channel numbers, and if the ONU downstream and upstream channel numbers match, the OLT sends that ONU its channel number (step **1006**). The ONU saves DFB laser setting parameters (e.g., TEC temperature or bias current values) in memory (step **1007**). According to some embodiments, the setting parameters are stored in a table (e.g., table **105**A or **105**B) residing in memory (e.g., RAM **102** or Data storage device **104**). The ONU then enters a registration status (step **1008**).

Section B: ONU DFB Tunable Transmitter Self-Characterization and Channel Set-Up (where Downstream and Upstream are not at the Same Channel).

With regard to FIG. **11**, a flow chart illustrating an exemplary ONU DFB Tunable Transmitter Self-characterization and Channel Set-Up procedure **1100** is depicted according to embodiments of the present invention, where Downstream and Upstream are not at the same channel. According to some embodiments, if the ONU downstream and upstream are not at same channel, the OLT sends its upstream channel number (e.g., the receiving channel transfers an upstream channel number to a downstream channel) to the ONU (step **1101**). After the ONU receives its current upstream channel number, the ONU determines what temperature change to use to tune its wavelength to another upstream channel (step **1102**). In one example, an ONU increases or decreases the temperature by 7.4 C.° and moves its wavelength to the two adjacent channels. The ONU sets the DFB laser TEC temperature to a new value and waits for a next channel-set-up time slot (step **1103**). The ONU repeats the steps of Section A above and the previous steps of Section B until it locates its upstream channel setting parameters (step **1104**). The setting parameters are saved into memory (e.g., saved in a table resident in memory) (step **1105**). The ONU has finished its DFB tunable laser self-characterization processing and the upstream channel setting parameters and setting parameters for one downstream receiver channel are saved into memory.

Section C: OUN DFB Tunable Transmitter Self-Characterization and Channel Set-Up (where Upstream Messages have Crashed).

When two or more ONU upstream messages overlap at the OLT side (e.g., two upstream lights in one upstream channel in Section A), that channel receiver is not able to read the entire message and is not able to send the ONU its information (e.g., channel number). Average optical power from the OLT receiver optical power monitor indicates a high average optical power value. If the average optical power value is greater than the receiver optical power sensitivity average optical power value, the OLT detects that the upstream signals have crashed. The OLT informs that channel's ONUs that the upstream channel has crashed. After the ONUs receive the message, the ONUs attempts the channel again after the next Checking and Matching window comes with a random delay for each ONU until they enter registration status.

Section D: ONU DFB Tunable Transmitter Self-Characterization and Channel Set-Up.

The upstream ONU DFB laser wavelength may not fall into the pass-band of the demultiplexer at the OLT side after following the procedures detailed above in Section A. When an upstream signal is outside the pass-band of a DeMUX, the upstream signal may be too weak to determine its channel for the OLT. When the receiver average optical power value is below a certain threshold, the OLT does not send downstream information. According to some embodiments of the present invention, the ONU does not receive any response for its upstream messages and determines that it is not on the correct upstream channel. The ONU tunes its DFB laser wavelength by changing the TEC temperature. The temperature change is determined by the cyclic DeMUX pass-band width at the OLT side. The laser frequency shift value may be made less than the pass-band width of the DeMUX and larger than rejection band width (e.g., channel space frequency minus the pass-band width) by changing TEC temperature. For example, where the channel space is 100 GHz and the DeMUX pass-band width is 60 GHz, the frequency shift is between 40 GHz and 60 GHz. The ONU sets the DFB laser to the new TEC temperature and waits for a next channel set-up time slot. The ONU then repeats Section A channel set-up procedures.

Section E: ONU Completing Tunable Receiver Channel Set-Up.

After finishing an upstream channel set-up procedure, an ONU receiver has also completed one downstream channel set-up. The procedures of this section finish the set-up for the other ONU receiver downstream channels and complete the downstream receiver set-up table. The ONU first sets its tunable receiver to another downstream channel. The ONU repeats the DFB tunable laser channel set-up procedures (e.g., the procedures of Section A or Section B) and finds the tunable filter setting downstream channel number. The ONU saves that channel tunable receiver setting parameters into a table. The ONU then sets its receiver to another channel. The above steps are repeated and the ONU determines downstream channel setting parameters for its tunable receiver and saves the setting parameters into the table. The ONU has finished its upstream and downstream channel setting processing at this time.

Section F: DFB Laser Wavelength Tuning Experimental Results by Changing TEC Temperature Experimental Conditions.

With regard to FIG. **6**, exemplary DFB laser wavelength results based on TEC temperature changes are disclosed according to embodiments of the present invention. The DFB laser output power is maintained constant as the TEC temperature changes, where the vertical axis represents DFB laser wavelength and the horizontal axis represents TEC temperature in Celsius units. As depicted, wavelength shift has a linear relationship with TEC temperature change within the DFB laser working temperature range. According

to some embodiments, the laser wavelength increases 0.1077 nm per one degree temperature increase. For example, for 0.8 nm wavelength tuning, TEC temperature change is 7.4 C.°, and for 0.32 nm wavelength tuning, TEC temperature change is 3.0 C.°.

DBR Tunable Laser-Based ONU Application for Flexible Grid TWDM-PON System

A three-section DBR tunable laser is a cost-effective light source for the ONU of the disclosed Flexible Grid TWDM-PON. Furthermore, it is not necessary to characterize the DBR tunable laser for ONU transmitter channels and wavelengths during manufacturing. There are several wavelengths that fall into every cyclic DeMUX channel because the DBR laser has a large wavelength tuning range (e.g., >10 nm). Also, the DBR laser mode wavelength space for two DBR bias current values can be made to nearly match the DeMUX channel space. This simplifies tunable ONU registration.

According to some embodiments of the present invention, the basic DBR laser has the following specifications. The laser wavelength falls into a specific wavelength range, such as DBR. According to some embodiments, the phase bias current is zero and the wavelength falls into a wavelength range between 1541 nm and 1538 nm. The laser wavelength tuning range is greater than 10 nm with a DBR bias current less than 20 mA. The laser phase bias current value is less than 1.5 mA for the first wavelength tuning cycle. The laser average output power is greater than 5 dBm, SMSR is greater than 35 dB, and TEC is 30 C. The laser modulation response bandwidth is greater than 2.5 GHz.

Tunable ONU DBR Laser Self-Characterization Before Registration in Flexible Grid TWDM-PON System

According to some embodiments of the present invention, a DBR (distributed Bragg reflector) laser backside photodiode detector (PD) power monitor is used to find the laser DBR bias current values for the modes with two or more different phase bias current values. For one phase bias, the laser has a set of DBR bias values, which are related to the laser modes (e.g., wavelengths). For another phase bias value, the laser has a different set of DBR bias values which are related to another set of wavelengths. The two sets of DBR current bias values are stored into memory. These two sets of DBR values correspond to two sets of laser wavelengths. The wavelength value differences between the sets of wavelengths which are related to the same laser mode are decided by the difference between the two phase bias currents. The two phase current values make the related DBR wavelength mode shift larger than the rejection band between the two channels of cyclic DeMUX and less than the pass band of cyclic DeMUX. DBR-based tunable ONU now is ready to be connected to system for registration processing.

Section G: DBR-Based ONU Tunable Transmitter Channel Set-Up I.

An exemplary ONU tunable transmitter channel set-up procedure **1200** is depicted in FIG. **12** according to embodiments of the present invention. According to some embodiments, to perform channel checking and matching, the receiver is first set to a downstream channel (step **1201**), and the OLT synchronizes its transceivers (step **1202**). A timeslot (e.g., time window) is opened for channel checking and matching processing for the channels (step **1203**). After a new ONU receives a channel checking message from one of the OLT channels, including its downstream channel ID, the ONU turns on its DBR laser (step **1203**). The ONU transmitter sends an upstream message and sends the OLT its identification and the downstream channel ID for its receiver (step **1204**). The OLT checks its downstream and upstream channel numbers (step **1205**). If the downstream and upstream of the ONU are at the same channel, the OLT sends the ONU its channel number (step **1206**). The ONU saves the DBR transmitter setting parameters (e.g., gain, phase, DBR bias current values, and TEC temperature) into the table and proceeds to a registration status (step **1207**). When another channel set-up time slot comes, ONU finds another DBR transmitter bias parameters for another upstream channel. If the upstream and downstream channels are not at same channel, the OLT sends upstream channel information to the downstream channel transmitter and that downstream channel transmitter transfers the information to the ONU. The ONU then saves these parameters into the table until the DBR mode settings are complete. Once this process is completed, the ONU has found the upstream channel setting parameters and finished its upstream channel setting processing.

Section H: DBR-Based ONU Tunable Transmitter Channel Set-Up II.

Still with regard to FIG. **12**, following the DBR-Based ONU Tunable Transmitter procedure of Section G, according to some embodiments of the present invention, if the ONU downstream and upstream channels are not matching, the OLT transfers the ONU upstream information to its downstream transmitter, which is related to the ONU receiver receiving channel, and that OLT transmitter sends the ONU its upstream and downstream channel numbers (step **1208**). The ONU saves the upstream tunable laser setting parameters (e.g., gain, phase, DBR current, and TEC temperature) and the receiver downstream channel setting parameters into a table resident in memory (step **1209**). When a next channel setting message (e.g., a new time slot) arrives, the ONU repeats the processing steps of Section G disclosed above (step **1210**). If the ONU downstream and upstream channels are not matching, the previous processing steps of this section are repeated. The ONU completes the DBR laser channel setting parameters and save the setting parameters into a table resident in memory.

Section I: The DBR-Based ONU Tunable Transmitter Channel Set-Up III.

When two or more ONU upstream messages overlap at an OLT receiver channel, the OLT is not able to receive all messages from the ONUs. Based on the average optical power the receiver receives, the OLT determines that the upstream message has crashed. The OLT broadcasts an upstream crashed message and inform that channel's ONUs of the crash. After the ONUs receive the message, the ONUs attempts the same channel during the next checking and matching window after a random delay. The ONUs then follow the procedures of Section G disclosed above.

Section J: DBR-Based ONU Tunable Transmitter Channel Set-Up IV.

When the upstream signal is too weak to determine its channel for the OLT, the OLT does not send a downstream message, and the ONU does not receive any response to its upstream message. The ONU determines that it is not on the upstream channel, and the ONU upstream wavelength may fall into the rejection band of the cyclic DeMUX. The ONU switches its DBR laser and phase bias current values simultaneously and makes the laser wavelength shift larger than its channel rejection bandwidth. The ONU repeats this step until it determines its upstream channel. On average, the ONU upstream wavelength located its upstream channel range on the second attempt. The ONU then waits for the next downstream timeslot for a channel checking and matching message.

Section K: ONU Tunable Receiver Channel Set-Up.

After finishing upstream channel set-up as described above, an ONU receiver has completed one downstream channel set-up. According to some embodiments, the following procedure completes the ONU receiver downstream set-up for all other channels (this processing also useful for DFB laser based ONU tunable receiver channel set-up). The ONU sets its tunable receiver to another downstream channel. It repeats DBR laser channel set-up of Section G or H and determine the tunable filter setting downstream channel number. The ONU saves that channel tunable receiver setting parameters into a table resident in memory. The ONU then sets its receiver to another channel. The above steps are repeated and the ONU finds all downstream channel setting parameters and save the setting parameters into the table. ONU has finished its upstream and downstream channel setting processing.

Section L: Three-Section Tunable DBR Laser Mode Space Optimization for Flexible Grid TWDM-PON System

According to some embodiments, after the DBR laser-based ONU determines one upstream channel, the ONU may find its other upstream channels automatically. The DBR laser mode space is nearly uniform, and the DBR laser mode space value may approximate the near upstream channel space value. After one upstream channel is determined, the closest bias current value (e.g., DBR current bias increasing direction) of the DBR laser corresponds to its adjacent shorter wavelength channel. For the DBR bias current decreasing direction, the immediate front DBR bias current value is related to its adjacent longer wavelength channel. Therefore, if one DBR bias current value produces the laser wavelength at channel 1, the next closest DBR bias current value tunes the laser wavelength to channel 2, and its immediate front DBR bias current value tunes the laser wavelength to the last channel of the cyclic demultiplexers for the same DBR laser phase bias current value.

With regard to FIG. **7**, exemplary DBR laser wavelength tuning and hopping results with DBR bias current increasing are depicted according to embodiments of the present invention. The DBR laser mode hoping step results, from 0 mA to 12 mA, are: 0.721 nm 0.7327 nm 0.7393 nm 0.749 nm 0.756 nm 0.715 nm 0.72 nm 0.736 nm 0.7372 nm 0.7468 nm 0.7461 nm (where DBR section is biased at the middle of each stage).

DBR Laser-Based Tunable ONU Upstream Channel Alignment Experimental Results

With regard to FIG. **8**, an exemplary set-up diagram is depicted according to some embodiments of the present invention. A 4-channel cyclic demultiplexers (DeMUX) **803** is used. Its passband width is 90 GHz for 1.0 dB and its insertion loss is about 3.0 dB. The DBR laser **808** connect to cyclic DeMUX **803** input port and the DeMUX **803** output ports are connected to optical spectrum analyzer (OSA) **802**. A computer **801** is connected with OSA **802** and a laser driver **804**. The computer controls the laser gain **805**, phase **806**, and DBR bias current **807**. An OSA (e.g., OSA **802**) reports output power from the cyclic DeMUX **803** output channel to the computer. Matlab codes are used to report output power, according to some embodiments.

With regard to FIG. **9**, a chart illustrating exemplary DBR tunable laser upstream channel alignment results for 4 channels according to embodiments of the present invention. The bit-error rate (BER) after C-DeMUX is illustrated along the vertical axis, and the DBR Bias Current in mA is illustrated along the horizontal axis under the following conditions: Gain is 48 mA, Phase is 0 mA, Vm (RF modulation voltage) is 1V, and optical power is about −30 dBm. The Channel 1 results are depicted by the square markings, the Channel 2 results are depicted by the triangular markings, the Channel 3 results are depicted by the circular markings, and the Channel 4 results are depicted by the diamond makings.

Embodiments of the present invention are thus described. While the present invention has been described in particular embodiments, it should be appreciated that the present invention should not be construed as limited by such embodiments, but rather construed according to the following claims.

What is claimed is:

1. A method of performing online receiver characterization for a tunable optical network unit (ONU) having matching upstream channels and downstream channels, the method comprising:

tuning an optical receiver of the tunable ONU to a first downstream channel;

synchronizing one or more transceivers at an optical line terminal (OLT);

opening a timeslot for channel checking of one or more upstream channels;

receiving a channel checking message from the OLT comprising a downstream channel identifier (ID) at the tunable ONU;

activating a laser at a pre-set temperature;

sending an upstream message from the tunable ONU to the OLT, wherein the upstream message comprises the downstream channel ID and an identifier associated with the tunable ONU; and

verifying the downstream channels and upstream channels at the OLT based on the downstream channel ID and the identifier associated with the tunable ONU.

2. The method of claim **1**, further comprising sending a channel number from the OLT to the tunable ONU.

3. The method of claim **2**, further comprising entering the tunable ONU into a registration status.

4. The method of claim **1**, further comprising simultaneously adjusting a distributed Bragg reflector (DBR) laser and a phase bias current value of the tunable ONU to locate an upstream channel.

5. The method of claim **4**, wherein the simutaneously adjusting the DBR laser and the phase bias current value produces a laser wavelength shift that is larger than a channel rejection bandwidth of the ONU.

6. The method of claim **1**, further comprising saving channel setting parameters in a memory resident table.

7. The method of claim **6**, wherein the channel setting parameters comprise at least one of gain, phase, distributed Bragg reflector (DBR) current, and thermoelectric cooler (TEC) temperature settings.

8. A method of performing channel checking and matching for a tunable optical network unit (ONU), the method comprising:

receiving a first channel number from an optical line terminal (OLT) at the tunable ONU;

tuning a downstream channel of the tunable ONU based on the first channel number;

waiting for a channel checking and matching message;

determining if the downstream channel and an upstream channel of the tunable ONU are a same channel number;

responsive to the downstream channel and the upstream channel of the tunable ONU being a same channel number, entering a registration status at the tunable ONU; and

responsive to the downstream channel and the upstream channel of the tunable ONU being of different channel numbers:

transferring upstream information from the tunable ONU to the OLT, wherein the upstream information relates to an ONU receiving channel;

receiving a second channel number from the OLT at the tunable ONU;

tuning the tunable ONU based on the upstream information and/or the second channel number; and

entering the registration status at the tunable ONU.

9. The method of claim **8**, wherein the tuning the tunable ONU based on the second channel number comprises tuning a transmitter of the tunable ONU to a new upstream wavelength.

10. The method of claim **8**, wherein the tuning the tunable ONU based on the second channel number comprises tuning a receiver of the tunable ONU to a new downstream channel.

11. The method of claim **8**, wherein the tuning the tunable ONU based on the second channel number comprises:

receiving a tuning command from the OLT at the tunable ONU; and

performing the tuning command at the tunable ONU.

12. The method of claim **8**, further comprising saving channel setting parameters in a memory resident table.

13. The method of claim **12**, wherein the channel setting parameters comprise at least one of gain, phase, distributed Bragg reflector (DBR) current, and thermoelectric (TEC) temperature settings.

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